Monitoring of landslides with mass market GPS: An alternative low cost solution

A low cost solution as an alternative to traditional mobile mapping system

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Abstract: *Mobile mapping vehicles (MMV) are the most used technology to acquire spatial information (images, cloud of points) but it is very expensive (>100M€) and it can be used only by "expert" users. Considering the existing MMV, a low cost (<40k€) solution have been realized, using 3 GNSS receivers, 3 webcams and 1 IMU. All sensors are on a rigid and calibrated platform, which can be installed on every terrestrial vehicle. The system is immediately operative after a calibration, using a particular calibration field.*

Images are georeferenced considering the positions and attitude estimated by GNSS and IMU solutions, also during the GNSS outages.

A combined GNSS/IMU solution is considered to compensate the IMU drifts; in particular, a loosely coupled solution is been developed and applied in this case.

Dedicated software devote to the acquisition, the synchronization, the elaboration and the plotting of the data have been developed, paying attention to the algorithm with respect to sensors integration and photogrammetric aspect.

Using this low cost system is possible to obtain the coordinate of the interest points (i.e. road signs) with a centimetric accuracy.

Keywords: *Mobile Mapping, Low cost, GNSS/INS integration, Kalman Filter, road cadastre*

1. Introduction

The Italian Ministerial Decree (MD) of June 1 2004 obliges the organisations in charge of roads to have a cadastral map of the roads. In Piedmont, there are about 2300 km of regional roads. There are various ways of carrying out high production surveys and one of these is based on surveys taken from Mobile Mapping Vehicles (MMV). This technique was first introduced in the eighties and it makes use of road vehicles equipped with GNSS receivers, an Inertial Measurement Unit (IMU), an odometer and high resolution camcorders. In some cases, these vehicles can be integrated with profilometers to measure the roughness of the road surface and with laser scanners to integrate the survey of the longitudinal and the cross sections of roads, bridges, galleries, retaining walls and other.

The survey consists in the determination of the road centre line axis as the average of two recordings measured going back and forth with the cinematic GNSS and IMU: the MD has fixed a tolerance of 1 m. The survey of pertinent features of the road such as intersections, entrance ramps, protection barriers and horizontal, road signs and painted road markings are foreseen for the creation of a road cadastral map. These details are surveyed through the georeferencing of the images from the camcorders, which are usually acquired in constant spatial intervals, together with the parameters of the position and attitude of the vehicle. The tolerance allowed by the MD for the survey of the pertinent features is 2 m. The GNSS-IMU integration for the calculation of the position and attitude angles of the vehicle is based on Kalman filter which allows the position of the vehicle to be surveyed, even in the absence of a GNSS signal. The modelling of the errors in the IMU inertial equipment is determinant to obtain a good solution, especially for temporal gaps in the GNSS data, as a consequence of urban canyons, tunnels etc.

Different vehicles equipped with sophisticated and expensive sensors exist in Italy and throughout the world. The objective of this work was to create a low cost equipment (< 30 k€) that could be installed on any type of vehicle. The purpose is both that of being able to carry out surveys with accuracy specified in the DM without large investment, and of creating a suitable means for the geometric testing phase of the surveys carried out by the contracting companies.

2. Description Of The MMS

Today the MMSs available on the market are surely considered into the category "high cost", because the average cost is usually greater than 50000 €; the number of user and the possible interested sectors are limited by this factor. The actual commercial solutions are complete, very specific and particularly related to the typology of relief.

The objective of this research is the development of a prototype for a MMS that can be proposed for a manufacturing production, based on the use of low cost sensors such as digital cameras, GNSS receivers and MEMS inertial sensors. This project has developed a multi-sensors system devotes to data acquisition that has the follow characteristics:

- low cost (< 30000 €);
- small dimensions and transportable;
- flexible, it will be installed without problems on different vehicles (rigid platform);
- adaptable, it has to guarantee different level of precision and type of information (position, attitude, images, clouds of points) through an integrated modular structure;
- user friendly, user not specialized can use this system eventually with a limited times of training.

The proposed low cost mobile mapping system (LC-MMS) is composed by:

- 3 GNSS L1/L2 geodetic receivers (Leica ATX1202GG);
- 3 webcams (Logitech Quickcam Pro 900)
- 1 or 2 IMUs (Crossbow IMU 700CA and Crossbow IMU 400CC)

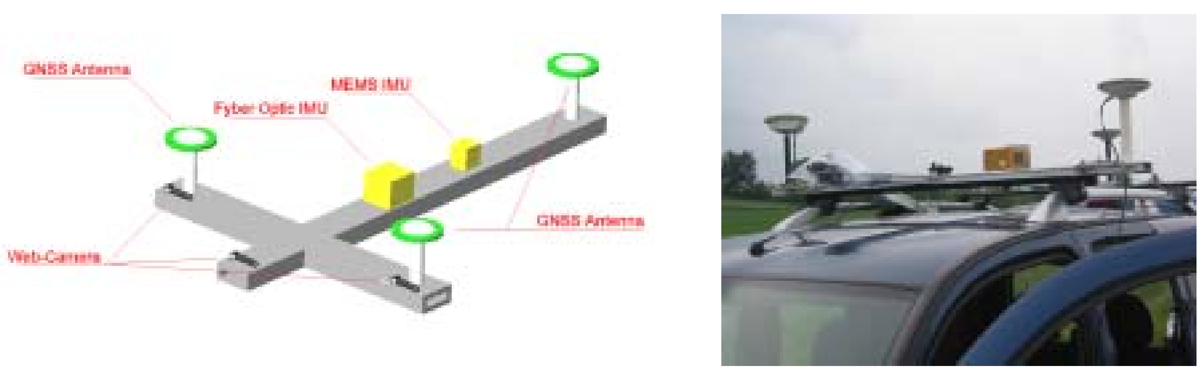

Fig 1. Layout of the system and its configuration

The system would need an initial calibration that would make use of some specifically prepared calibration filed. The purposes of this operation are:

1) estimating the internal orientation parameters of the webcams and of the distortion curve of the lens;

2) estimating the external orientation parameters between the lens axis of the webcams and the instrumental reference system (body) materialised according to the position of the GNSS antennas.

The images are then put in a "ground" reference system, starting from the position of the GNSS antennas integrated with the acceleration and angular velocity data supplied by the IMU.

The nominal accuracies that can be reached in the surveying of centre line road axis and of the details from the images are, however, considered. The accuracy of the position of the antenna that can be reached with GNNS, kinematic RTK or in Post Processing is of a centimetre type for solutions with fixed internal ambiguities. If we consider the attitude of the vehicle to be known only from measurements of the 3 GNSS receivers to which a reasonable precision of 3 cm each can be attributed, placed on a vehicle at a known distance, the error in the determination of the roll, pitch and heading angles is lower than 2.1 gon. If we consider a taking distance of the camera of 20 m, the corresponding linear error becomes 67 cm (compatible with the tolerance requested by the Italian MD).

SYSTEM CALIBRATION

The Mobile Mapping System requires to define some reference systems and to estimate the transformation parameters which allow to pass from a reference system to another one.

In our case, four reference systems are identify:

- (RS1) the mapping reference system (E, N, h), which is green in Fig. 2 is the standard UTM WGS84 with ellipsoidal height: if a local model of geoid undulation is available, the orthometric height can be easily calculated. The final product is the recording of point coordinates of objects mapped in this reference system;
- (RS2) the body system (x_b, y_b, z_b), which is red in Fig. 2, is defined using the GNSS/IMU instruments. In particular, in this case, the origin is fixed in the stern bottom of antenna mount, the y_b-axis is defined from the origin to the prow bottom of antenna mount and the z_b-axis is not necessarily vertical but belongs to a vertical plane that contains y_b. This system is fixed onto the car;
- (RS3) the camera system (x_c,y_c,z_c), which is blue in Fig. 2, is the internal camera system (single camera system or the model system using two cameras in stereoscopic view) defined according to photogrammetric rules.

The z_c-axis coincides with the principal axis of the digital camera directed towards the road, the x_c-axis is in the same direction as the rows of acquired digital images;

- (RS4) the plotting system (x_{pl}, y_{pl},z_{pl}), which is yellow in Fig. 2, is the local system used to plot the point coordinates of the mapped objects. This system is joined to the car (and it can move with it). The z_{pl}-axis coincides with the vertical for the bam of stern GNSS antenna, the y_{pl}-axis is the projection of y_b onto the horizontal plane that approximates the road surface (in a horizontal situation).

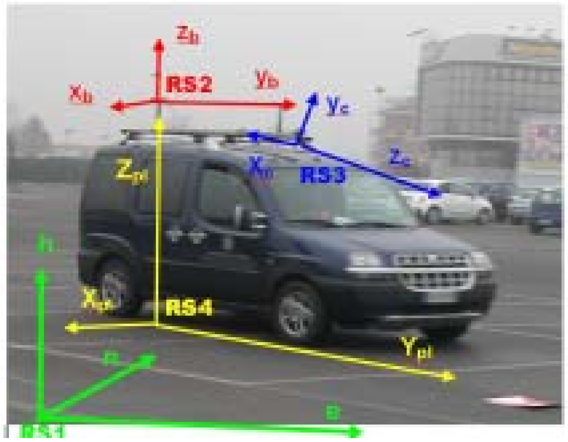

Fig 2. Reference systems of MMS

The used transformations between these reference systems are:

- RS2toRS1, a 3D roto-translation with a scale factor (7 parameters);
- RS4toRS2, a 3D roto-translation without a scale factor (6 parameters);
- RS3toRS4, a homographic projective transformation, if it uses a plane approximate approach (8 parameters and some additional parameters for optical camera calibration);
- RS3toRS4, the collinearity equations, if it uses a rigorous photogrammetric approach (9 parameters for each camera and some additional parameters for optical camera calibration).

The RS2toRS1 transformation is available using GNSS/IMU integrated observations and a limited interpolation. Instead, the other transformations require various parameters that must be known to permit the correct use of the MMS: a specific system calibration was needed to resolve this problem. After the calibration procedure, it was possible to use the proposed LC-MMS for these main functions:

- the direct survey of road paths using GNSS/IMU data, with measurements of lengthwise slope, road axes etc.;
- the positioning (in RS1) of each significant point that is useful to describe road cadastral details by means of a photogrammetric procedure with camera data. It is possible to use a simplified procedure based on monoscopic plotting (road planar hypothesis) or a rigorous spatial resection based on stereoscopic on-track plotting algorithm (this will be attempted in the future);
- the recording of these coordinates in a digital way with associated coding and other attributes in a specific database structure (digital map);
- the rectification of some frames acquired by the video camera to generate a rectified image in RS1 of the whole surveyed road. In this way, the GIS application based on acquired data can be completed with a raster background that contains a metric photographic image.

A. Photogrammetric calibration of the webcam

A photogrammetric procedure was used to define the internal orientation parameters of the webcam and the optical distortion of its lens. This calibration was carried out for a particular focal lens of the webcam obtained with manual focusing and minimum zoom setting: in a practical acquisition, these properties must be set before the video is started, deactivating of automatic focussing and zooming.

A calibration network was created: 20 signalized control points were measured using a high precision total station and redundant space resection schema. The estimated accuracy was about 1 mm in 3D components. Therefore, 2 stereoscopic images of the calibration network were acquired at maximum hardware sensor resolution (1600x1200 pixels). The network points were plotted on the acquired stereo pair using automatic recognition for the initial position and Least Squares Matching for the final precise measurements. The data were inserted into a bundle block adjustment with additional self-calibration parameters (according to Brown distortion model). The estimated tangential distortion parameters (P1, P2, P3) and the affinity sensor deformations (A1, A2) are not meaningful different from 0 (Student test, 5%).

The entire procedure was repeated several times, with different camera positions on various days, but always with the same focus and zoom. The differences between the calibration parameters resulted to be not meaningful, thus demonstrating the substantial stability of a Logitech Quickcam Pro 9000 in static situations.

B. Reference system calibration

An opportune calibration stage of the MMS was carried out in order to determine the transformation parameters between the various reference systems. For this purpose, an other calibration field was defined, measured and used.

This network is composed by:

- 3 vertices for the definition of the RS1, measured with static GNSS observations referred to the permanent stations managed by the Politecnico di Torino (Fig. 3);
- the three positions, with the vehicle still, of the GNSS antennas with 3 prisms for the measurements. The positioning was carried out through the Leica SmartStation in connection with the RS1 vertices: in this way it was possible to procure data for the definition of the RS2 in relation to the RS1. The measurements were carried out in different load conditions in order to define the variations of the calibration parameters according to the variations in the load situations.
- 11 control points signalled through specific panels in wood attached to the road surface and surveyed using Leica SmartStation in connection with the RS1 vertex: in this way, it was possible to procure data for the definition of RS4;
- 5 added control points situated on the tripods and surveyed through the Leica SmartStation in connection with the RS1 vertices: in this way it was possible to procure the data for the definition of RS3;
- More than 50 points, generated by the intersection between the description lines of the car parks utilised as check points, to validate the determined solutions.

The parameters of the RS2 transformation into RS1 and RS4 into RS2 were determined through the measurements carried out on the basis of purely geometric considerations. The ground control points coordinates are introduced in a software tools package (called LCMMS – Low Cost Mobile Mapping Software).

C. Time synchronization

The time synchronization of the used sensors is a fundamental problem. If there is a time synchronisation problem, no plotting operation or trajectory comparison are correctly available. For example, if the time delay is equal to 0.1 s and the vehicle moves at 40 km/h, the planimetric error on the plotting point is about 1.1 m. The impossibility to have recourse to an hardware time synchronisation led the authors to propose an original solution for the time synchronisation of the frames acquired with the webcam to the GPS reference time.

Before the survey is started, the clock of the laptop PC (that manages the three webcams) is synchronized to the GPS time. However, this clock is not an atomic–based and a time delay can therefore occur. During the monoscopic plotting, the coordinates of several points are measured using the first approximation of the attitude and position interpolated on base of the GNSS/IMU data and the PC time of image acquisition.
It is possible to survey the coordinates of the same points considering different frames (in different instant) and calculate the differences between the various positions of each point: if these differences are greater than the tolerance, the time delay is not negligible. If we combine this information with the instantaneous velocities defined from the GNSS/IMU data, the time delay can be estimated using both classical statistical approach (least squares) and a robust approach (least median of squares). The time delay could be approximated considering a constant value or a polynomial function. If the acquisition length is not very long (<1.5h), a constant value is sufficient to define it. The time delay is used to modify the camera time that is, the time when the single frames are taken.

D. GNSS-IMU integration

The integration of GNSS and IMU data offers benefits for many aspects of navigation solution and overall survey quality, because of the improved accuracy and reliability. Improvements in the mathematical modelling and software implementation such as tightly-coupled solutions make the use of the available information very efficient, especially for poor GNSS solutions. However, experience has shown that the use of these sensors and algorithms is not always sufficient to guarantee a fault tolerant system. Sometimes, error caused by outliers or residual model errors, even in only one of these sensors, can lead to fault-correct estimates of positions or attitudes.

This is particularly true in the case of GNSS outages or changes in GNSS constellations which often result in sudden shifts in the trajectories. If the two system components (GNSS and IMU) do not agree, the weights could be adjusted in the filter to minimize the contribution of erroneous data. With only two data sources available, deciding which data are wrong may not be feasible. Due to the error characteristics of the low-cost IMU, however, the system often relies primarily on GNSS data; the relative weighting of IMU and GNSS data therefore favours the latter as long as their quality is believed to be accurate.

If GNSS outages are long and severe, drift errors of the IMU become too large and the accuracy of the positioning data decreases. This may happen, for instance, in city downtowns, where the operating speed is sometimes slow because of the traffic (therefore outages last longer), along narrow streets where buildings are very close to the road, along tree-lined avenues or country roads, in road sections through forests, tunnels, etc.

Our realized integration algorithm, based on Kalman filter, allows to estimate the IMU attitude corrections using a GNSS multi-antenna system. This computation is particularly important, especially when low-cost inertial sensors are used, with high gyroscopes drifts, even exceeding 1°/s.

At the end of the Kalman filter, it is possible to refine the solution of the previous epochs with a backward procedure called smoothing. This procedure at each epoch regards the information deriving from all the measurements, and computes a navigation solution similar to that which would have solving the problem with the Least Squares method. An alternative procedure may be to use the information collected through the Kalman filter, backward adjusting, during the smoothing process, the effects of the residual accelerometers and gyroscope biases. This novel procedure of back-propagation of the residual bias was implemented in an our dedicated software and it is called Back-Propagation Smoother.

3. Management of the system

Our mobile mapping system is currently composed of different sensors managed by various laptops. Excluding the GNSS receivers that are able to collect the raw data by themselves, the other devices need to have a PC to set and to record the data. This problem has been solved developing several homemade software tools, writing in Matlab and Fortran languages.

A. Acquisition of the image frames

A special tool has been created in order to have an integrated system devoted to managing the webcam, collecting the raw data and control of time acquisition quality. At the end of the video, a quality control of the acquisition stability is carried out to estimate the real values of the webcam rate acquisition and to evaluate the effective regularity of data acquisitions.

Before starting, the resolution, the frame rate, the acquisition length, the image file names, and the time file have to be defined. Then, the acquisition can be started. A time file produced by the software includes the time of the first acquisition and the differences between each image and the first one. The summary of the quality control appears in a two graphs when the acquisition is terminated.

B. Attitude and trajectory definitions

The images can be georeferenced considering the position and the attitude of the camera. These values can be estimated considering both IMU and GNSS data. The three attitude angles can be also calculated considering the GNSS. The positioning is determined using two possible solutions:

- real time kinematics;
- post-processing kinematics.

The first solution foresees as is well known, that the position is estimated in real time: in this case, the corrections are estimated considering a model which derives from a RTK network of permanent stations. An experimental network exists in Piedmont that is composed of 15 permanent stations (fig. 3). A control centre which manages this network has been installed at the Politecnico di Torino.

An original package of utilities was developed to estimate the vehicle attitude using both the GNSS and the IMU measurements, using the GNSS measurements to compensate the IMU drifts and providing a seamless solution, also if the GNSS signal is not available.

Considering the camera time as the reference time where the image is captured, it is possible to interpolate and to define its position and attitude. There are different interpolation models, but not all are appropriate to define a kinematic trajectory. Spline interpolation is appeared as the more appropriate in this case.

C. Trajectories comparison

The same part of the road was covered several times and the coordinates that were obtained in a kinematic mode were compared in order to evaluate the accuracy of the survey of the centre line road axis,

A specific software tool was set up to determine and verify the road axis with the intent to:

1) determine the mean axis of a series of points surveyed going back and forth;
2) determine the off-lines between a trajectory that has to be verified and a reference one.

The errors were basically due to two factors:

- errors in the kinematic GNSS positioning;
- accuracies in the centred guide.

In the test carried out, the mean value of the planimetric discrepancies is equal to -7 cm with an RMS of 56 cm. The tolerance of 1 m on road layouts seems reachable with an ordinary guide bar, on condition that the fixing of the phase ambiguity is reached.

D. Low Cost Mobile Mapping Software (LCMMS)

The authors have developed a software tool package (LCMMS) which makes several functions available for the calibration, management and use of acquired data. LCMMS allows the following functions:

- to define the photogrammetric calibration parameters of the used camera in this way being free of the specific video camera that was used. These parameters must be defined “a priori” through specific photogrammetric procedures;
- estimate the simplified transformation (homograph) between the camera system and the plotting system
- define the parameters of the spatial roto-translation which transforms the plotting system into the body;
- measure the coordinates of significant points for the application of road cadastral maps with opportune coding and other connected attributes (Fig. 4).

The user can:

- visualise the images that make up the acquisition frame;
- move the cursor into the 3 graphic windows (scroll, image and zoom) and directly read the coordinates of the identified point (on the road);

- move forward and back inside the film, a photogram at a time or quickly
- measure and record (red button in fig.4) the map coordinates of the significant points;
- associate codes and various attributes in a real database;
- generate the rectified images of the chosen images, limited to 20 m in front of the vehicle,

already directly georeferenced in the map system.

4. Test Fields

A. Survey

The described system and procedures were verified in the field through the use of a test site situated near the calibration network site. About 70 check points were surveyed in the UTM WGS84 system (RS1 with precision of about 1 cm). using Smart Station and GNSS RTK in connection with the Politecnico di Torino test network of the permanent station

The calibration phase of the system was repeated and the parameters estimated at less than 1.5 cm in the translation and 0.1 gon in the rotation (RS4toRS2) were basically found to be unvaried. A substantial stability of these calibration parameters at a distance of about 15 m can therefore be observed.

B. Data Acquisition

The instrumentation was arranged for the acquisition of the data according to the following sequence:

- launching of the acquisition from the 3 GNSS receivers with a frequency of 5 Hz. The first 10 minutes of GNSS acquisition was performed with the vehicle still, in order to be certain of a correct initialisation;
- synchronisation of the clock of the laptop PC that manages the IMU sensor to the GPS time through a GPS Garmin receiver and NMEA-Sync software;
- synchronisation of the clock of the PC that manages the webcams to the GPS time through a GPS Garmin receiver and NMEA-Sync software, webcam configuration (with a resolution of 960 x 720 pixels, autofocus exclusion, choice of lowest zoom, nominal acquisition frequency configuration of 15 Hz) and launching of the acquisition through a dedicated software.

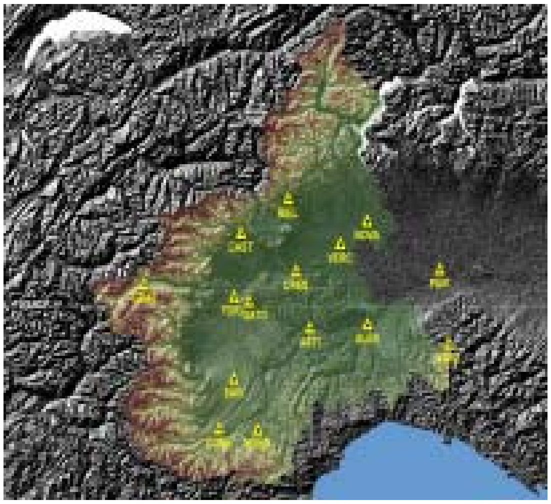

Fig. 3. The Piedmont network of GNSS permanent stations

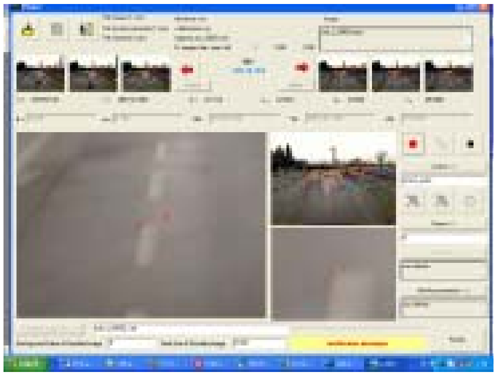

Fig. 4. LCMMS - software

The vehicle then began to move in the test area with numerous passages over the check points at a mean velocity of 11 m/s (about 40 km/h) for about an hour of acquisition of the webcams, in terms of control of the acquisition quality: the actual mean rate was 6.4 frames/s, that is an image on average each 1.7 m.

C. Preprocessing

The GNSS and IMU data were elaborated using both Waypoint Inertial Explorer software and our software of navigation, where the Back Propagation Smoother is implemented.

The final result is made up of the trajectory of the vehicle, the two trajectories of the three GNSS receivers (ahead and behind, on average a position each 2.2 m), the analytical and synthetic accuracy indices (on average 1.5 cm of standard deviation).

The GNSS receivers at the front and the attitude angles of the system were determined at the moment of acquisition of the images acquired by the webcam. In this way, it was possible to determine the RS2toRS1 transformation for each click instant of the various images, through an interpolation procedure elaborated in time with a homemade software. This interpolation is very limited, considering the high acquisition frequency of the navigation instruments. The collimations of about 20 check points were carried out utilising LCMMS software in the monoscopic plotting mode, with the vehicle still, and maximum discrepancies of about 25 cm were obtained in planimetry, thus basically demonstrating the correct functioning of the system.

The almost 70 check points were surveyed in the same way several times, at different times in the various passages that the vehicle made along the test site over a period of about 1 hour of acquisition (Set2). Table 1 shows the synthetic statistic parameters of the differences (Ve, Vn, Vh) determined between the coordinates of the check points in Set2 and Set1 (reference): the discrepancies in planimetry show very large values compared to the accuracy reached in a static situation, which would lead one to think there was a substantial synchronisation defect, in this case of the webcam acquisition management PC. Table 2 contains the effective values of discrepancies after the time correction. The values in height are basically very similar to the static situation as no great changes in height or slopes were encountered along the route travelled by the MMS.

Table 1. Discrepancies before the time delay correction

	Ve	*Vn*	*Vh*
Mean [m]	2.31	-2.15	-0,18
StDev [m]	2.21	2.19	0,15
Min [m]	-1.95	-3.01	-0,30
Max [m]	3.42	1.45	0.03

Table 2. Discrepancies after the time delay correction

	Ve	*Vn*	*Vh*
Mean [m]	-0,10	-0,13	-0,15
StDev [m]	0,10	0,05	0,03
Min [m]	-0,30	-0,21	-0,21
Max [m]	0,06	-0,06	-0,11

5. Final Results

The data acquired with the MMS system are fully acceptable, from the point of view of the tolerances that must be reached for road cadastral mapping purposes. Furthermore, when the differences (Set3-Set1) of the absolute value are plotted against the distance of the origin of the RS4 system (GNSS antenna in front of the vehicle), it is possible to note a substantially linear trend of the differences (Fig. 5.b). This trend was foreseeable in that the collimations are obtained from a visualisation of a digital image with constant pixel dimensions, on the sensor plane, but which are obviously variable on the road plane, according to a linear law. From the graph (Fig. 5.b) it is possible to define the limit distance for a correct collimation as about 15-16 m, limiting the errors that can be obtained to about 20 cm.

The rectified images were generated for about 1 frame per second (1 each 11 m) in the local system, RS4, and then georeferenced in the RS1 system. In Fig. 5.a it is possible to observe two rectified images that were obtained in this way, with overlapping of the relative check points. The substantial continuity of the delimitation lines of the visible adjacent car parks can be noted and this demonstrates the coherence between the obtained rectified images.

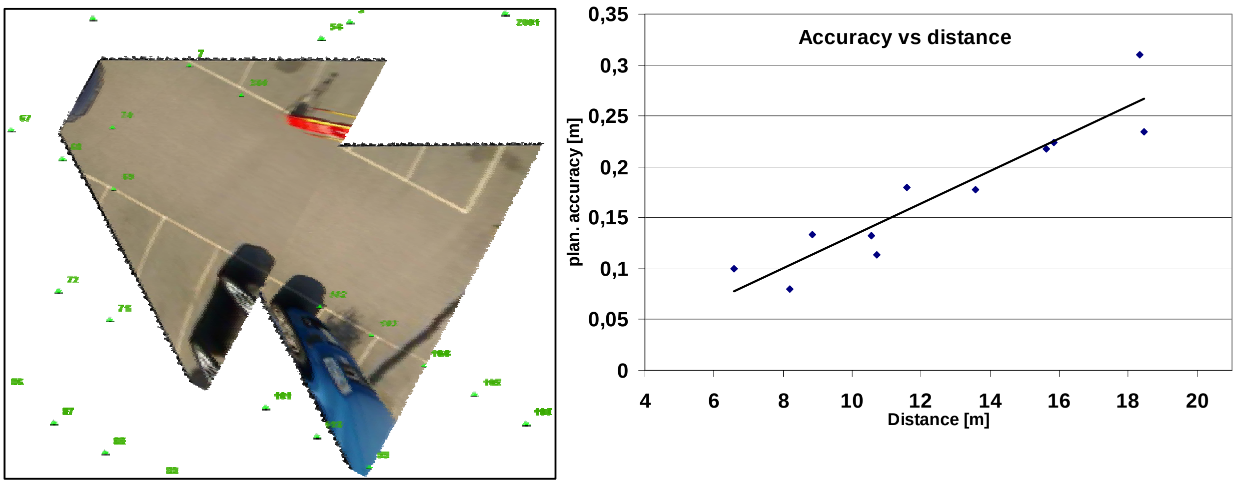

Fig. 5. Automatic mosaic of 2 rectified images (a) and relation discrepancies vs. distance (b)

6. Conclusions

The survey system that has been created seems to function and be suitable for reaching the precision requested by the Italian MD. The GNSS integration with the available IMU makes it possible to recuperate short length cycle slips (< 1 min) with a metrical precision that is compatible with the survey of the road axis. The solution adopted for the georeferencing of the images, at present of a monoscopic type, seems to be suitable for the surveying of the road details and opportunely calibrated USB webcam type cameras have been successfully used. These are commanded via software and have suitable acquisition rates to carry out a high efficiency survey.

This system is at present in an experimental stage: some improvement modifications are foreseen, such as the use of a more precise but cheap IMU (drift < 1°/hour) of less than 15 k€. The system would, however, still be considered part of the low cost category.

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